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# Asset management to support urban land and subsurface management

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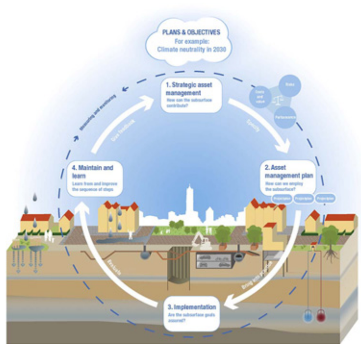
## HIGHLIGHTS

- Taking subsurface into account in urban areas avoids damage and adds value.
- Subsurface ecosystem services present value and can therefore be considered assets.
- Asset Management provides structure and transparency to subsurface management.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Pressure on urban areas increases by demographic and climate change. To enable healthy, adaptive and liveable urban areas different strategies are needed. One of the strategies is to make better use of subsurface space and its functions. Asset management of the Subsurface (AMS) contributes to this. Asset management provides transparency of trade-offs between performance, cost and risks throughout the entire lifecycle of these assets. AMS is based on traditional asset management methods, but it does not only take man-made assets in the subsurface into account. AMS also considers the natural functions that the subsurface, including groundwater, has to offer (ecosystem services). A Dutch community of practice consisting of national and municipal authorities, a consultancy-engineering and a research institute are developing AMS in practice in order to 1) enhance the urban underground space planning (using its benefits, avoiding problems) and 2) use, manage and maintain the (urban) subsurface and its functions. The method is currently still under development.



## 1. Introduction

World-wide the need for healthy, adaptive and liveable urban areas is increasing, as urban areas are growing in size and population. The proportion of the world's population living in urban areas will increase from 54% today to 66% by 2050 (United Nations et al., 2014). Next to demographic changes, climate change and the need for resource efficiency increase the pressure on the available space and the complexity to meet the needs in urban areas. One of the solutions is to make better use of subsoil and subsurface space and its functions. In this paper, we will use the word subsurface for everything below ground level: both the upper layer (soil) and deeper layers (subsoil) of the Earth's crust, including organic and inorganic material and groundwater. Because space below surface level is inefficiently used due to lack of spatial planning, promising (combinations of) subsurface functions are not utilized or damage occurs due to unexpected effects or interferences. To avoid this, sustainable integral management of the subsurface is needed. The main goals for sustainable and integral subsurface management are: 1) prevent unnecessary damage of both the subsurface and its (future) functions, 2) optimally utilize the opportunities of the subsurface and

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3) coordinate subsurface and surface-level activities. Asset Management of the Subsurface (AMS) can be a suitable instrument to achieve integral and sustainable subsurface management.

AMS is based on traditional asset management methods, but it does not only take the traditional man-made assets in the subsurface into account (e.g. infrastructure, sewer system, underground parking garage, cables). For AMS it is investigated if assets management is applicable for the often neglected but valuable functions of the subsurface as well (ecosystem services). The Millennium Ecosystem Assessment defined ecosystem services as "the benefits people obtain from ecosystems" (MA, 2005). According to Price et al. (2016), the benefits that society derives from the use of underground space can be considered as natural capital. Natural Capital is the sum of all the assets derived from the earth's environment, including those derived from soil, which are essential for people to live.

Since 2015, a group of subsurface managers of Dutch municipalities and the National authority are working together with a consultancy-engineering and a research institute in a Community of Practice (CoP) on AMS. They aim to answer the question: (How) can asset management be a way to improve the management of urban subsurface and its functions? Their main aims were to: Avoid damage of the subsurface and its (future) functions; Coordinate soil - subsurface and surface-level activities, and; Optimally use the opportunities of the soil - subsurface and maintain its functions. To achieve these aims, they promote aware management of both traditional assets in the subsurface as ecosystem functions. AMS can offer the municipalities a method that fits to their daily practice and operational management.

This article elaborates the findings of the CoP based on the practice of two municipalities and includes the organisational aspects of implementing AMS in the municipal operational management. The method is currently still under development.

## 2. Asset management

Asset management, following the ISO 55000 Family of Standards (ISO, 2014), is a coordinated activity of an organisation to realize value from assets. An asset is an item, thing or entity that has potential or actual value to an individual or organisation, by providing a service. A common objective is to minimize the whole life cost of assets, but there may be other critical factors such as risk or business continuity to be considered objectively in decision making. Therefore within asset management, costs, opportunities (value) and risks are balanced against the desired performance of assets, to reach the organisational objectives. In addition, asset management enables the application of analytical approaches towards managing an asset over the different stages of its life cycle - including design, realization, management & maintenance and disposal.

In many cases municipalities already apply asset management to manage and maintain objects and infrastructures that they own or are directly responsible for, such as roads, bridges, benches and sewer systems. For example, a municipality manages and makes their choices for maintenance of roads based on analysing and balancing the risk of accidents that can occur due to poor conditions of the surface, the costs to repair the surface, optimal functioning of the road and the life-span of the surface.

## 3. Asset management of the subsurface

The goal of AMS is to contribute to sustainable subsurface management, by supporting decision-making during the realization, management and maintenance of subsurface functions. A new aspect is that AMS not only includes man-made assets, but also includes the natural functions of the subsurface that can be considered and managed as assets providing value.

There are examples of considering subsurface in asset management. Shah et al. (2014), discuss how the subsurface and its interaction with transportation infrastructure might be considered in terms of sustainability, vulnerability and resilience, both now and in the future. They argue that effects of climate change demand more resilient asset management methods, which also consider the geotechnical assets (such as slopes, foundations) instead of just the infrastructure itself. It recognizes that the subsurface and constructions on and in it should be considered as a system. However, the subsurface functions such as carrying capacity are not counted as assets themselves. De Mulder and Pereira (2009) describe the beneficial function provided by the ground as a consequence of its properties and the processes that operate within it as 'geoassets'. Geoassets include functions such as provision of groundwater, natural attenuation through soils, energy and drainage. Metje et al. (2008), discuss the asset management of invisible, buried assets of utility distribution and collection networks. They advocate to locate, map and share information on buried utility services. Also Abspoel et al. (2017) focus on buried assets: pipeline networks for gas and water. They developed a model to better predict failure probability of a pipe at the required moment in time, using subsurface characteristics and variability. However, these studies were, unlike AMS, not considering the natural functions of the subsurface as assets, or they were not aimed at actual implementation of subsurface asset management in an organisation or municipal setting.

AMS is targeting local and regional authorities, active and responsible for the public area and its functions. As illustration: if a city's strategic goal is climate change adaptation, this can be translated to a task: take measures to avoid pluvial flooding. This can be achieved by increasing the volume of a sewer system but alternatively by using the water storage capacity of the subsurface. Both the sewer system and the water storage capacity of the subsurface contribute to the strategic goals and can be considered and managed as an asset.

### *3.1. Adjustments to asset management to be applicable to the subsurface*

For AMS, some important adjustments on traditional asset management are needed:

1) Consider the system instead of separate objects: the subsurface is a system, containing man-made assets, such as cables and underground parking garages. It also offers natural assets (ecosystem services) with (in-) direct value for the urban environment, such as water storage and temperature buffering capacity to be used for soil energy. These (natural and man-made) functions can co-exist, compete for underground space, or interfere with each other, leading to positive or negative effects. Therefore knowledge about this system is essential.
2) Shifting focus from maintaining objects to maintaining functions. In urban areas, the municipality is responsible for maintaining and managing essential functions for the public: such as ensuring dry feet and a save, clean, healthy and pleasant environment. These functions can be obtained both by man-made or natural assets. Consideration of the long term performance, risks, costs and benefits can support choices in how to provide specific functions with natural solutions, civil engineering or a mix.
3) Private versus public asset management. With traditional asset management, assets are generally managed by a public or private entity that is aware that it is responsible for managing and maintaining the asset and has direct benefits from this. This is often not the case in urban areas for functions of the subsurface. The subsurface and its functions that local authorities can utilize are often located in public area. However, the subsurface also accommodates privately owned assets such as cables and pipes. Also land ownership (privately owned land in urban areas) influences the ability of local authorities to make use of subsurface functions. This demands consideration of the distribution of costs and benefits of the management of subsurface assets and good interaction with stakeholders.
4) From lifecycle to land cycle. Where man-made assets have a specific life time and are considered from construction to disposal, functions of the subsurface are already there and when maintained well for "eternity". They do not need to be constructed and cannot be

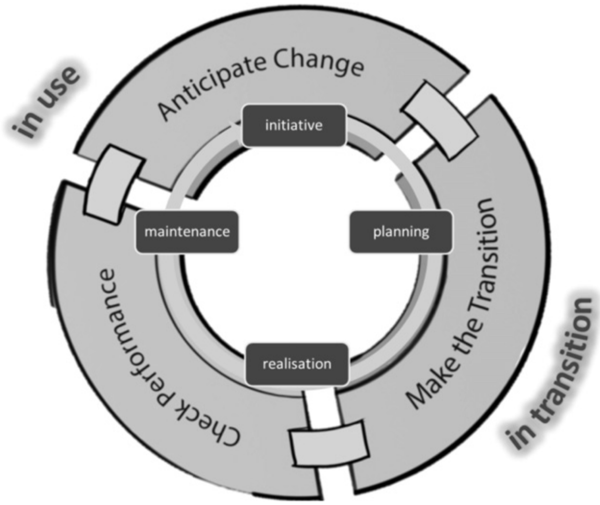


**Fig. 1.** The land cycle for asset management (based on Ellen et al., 2013).

disposed. Therefore they should be considered using a land cycle in which they perform their role (Fig. 1). The basic land use cycle (Ellen et al., 2013) consists of only two phases: 1) a use phase and 2) a transition phase. The end of a given use phase may or may not be a formal and adequate decommissioning of activities and clearance of the site. Ideally, it should be followed by the onset of development activities to realize subsequent use. The three land management phases consist of 1) anticipate change, 2) make the transition and 3) check performance. Project phases that can be connected with asset management tasks are initiative, planning, realization, maintenance. The goal of checking the performance of assets is to effectively maintain and manage the asset and create awareness in time that action is needed to fulfil the required function. This has strong similarities with the Deming circle plan-do-check-act (PDCA,), an iterative four-step management method used in business for the control and continuous improvement of processes and products (Deming, 1986).

The development of the AMS method by the CoP is based on existing methods developed for traditional asset management, underground urban planning and subsurface management and ecosystem services approaches. Four general requirements are set by the CoP for a useful AMS method; it has to contribute to 1) a structured and transparent method for subsurface management, 2) cost efficiency by reducing risks and costs, but also capitalizing (in-) direct values from the natural system, 3) a decision-support framework based on balancing value, risks and costs and 4) a common language for different disciplines and between different functions/levels to make options and choices understandable and transparent.

The basis for AMS is balancing the requested performance of functions of the subsurface with value or costs and risks. These main items are elaborated in more detail below.

### *3.2. Performance of functions of the subsurface*

The subsurface provides different functions that contribute to healthy, adaptive and liveable areas. Besides the function of providing space, which is mainly used for placing man-made assets, other functions provided by the ecosystem can be used. According to CICES, the

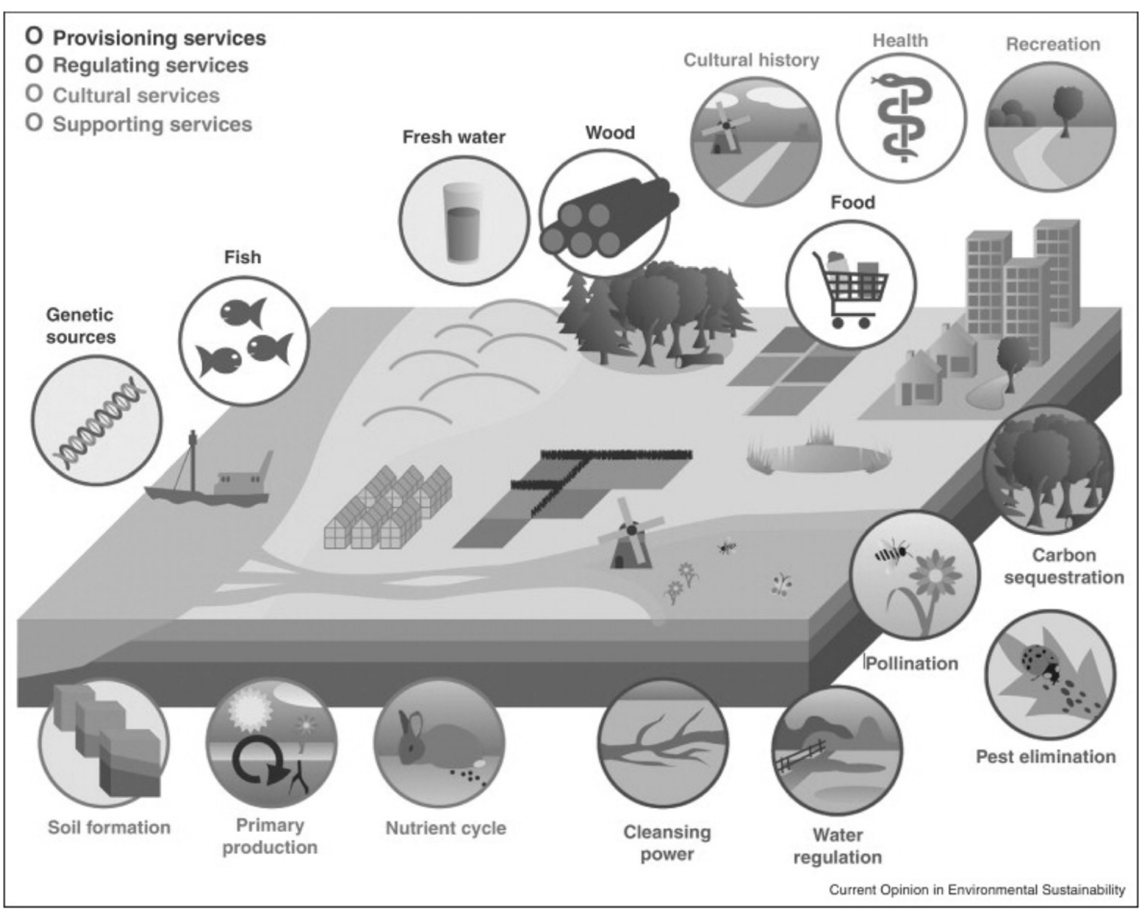


**Fig. 2.** Examples of ecosystem services in the Netherlands (Otte et al., 2012). This picture uses the four ecosystem categories of the Millennium Assessment (MA, 2005). Supporting services, as classified here as a different category, are mainly found in CICES [1] under the regulating and maintenance services.

Common International Classification of Ecosystem Services [1], ecosystem services can be divided in three categories: 1) provisioning services (e.g. availability fresh water, energetic content); 2) regulating and maintenance services (e.g. attenuation capacity of the subsurface, carrying capacity, biodiversity and habitat); and 3) cultural services (e.g. archaeology) (Fig. 2).

Depending on the characteristics of a location (e.g. soil type, elevation, groundwater level) and the objectives of the stakeholder(s), different functions can be demanded and obtained from the subsurface. In many cases, urban planners are not sufficiently aware of the potential that the subsurface offers (Norrman et al., 2015a, 2015b, 2016; Admiraal and Cornaro, 2016). Therefore, the first step in AMS is to analyse, depending on the ambitions and goals, which functions of the subsurface can be utilized and/or need to be maintained within an area. Consequently, the opportunities that the subsurface offers and challenges it poses need to be investigated and mapped, using area knowledge and available subsurface data and models. This should be communicated or done together with the people responsible for planning and/or maintaining urban space. Different methods have been developed to systematically analyse the potential of the subsurface for the urban system. A few examples of studies and methods considering the subsurface in urban planning are highlighted below.

The Urban SMS project was aimed at developing tools and instruments in pilots for urban subsurface management. The project advocates a broad view when considering subsurface functions for urban areas: from offering space and a basis for land use functions, storing and cycling nutrients to protecting archaeological treasures and so forth. Different IT (GIS) tools for the use within urban planning were developed as well as a handbook for municipal decision makers with practical advice how to implement a permanent management structure for soil protection within urban planning (Blumlein et al., 2012).

System Exploration Environment and Subsurface (SEES) is a method which supports and registers the knowledge exchange between experts of different fields, specialists of the technical and natural system and the aboveground specialists that represent the social-economic requirements (Hooimeijer and Maring, 2013). The method gives an overview of the urban system: it relates the above ground layers of people, cycles, buildings, public spaces and infrastructure to subsurface qualities divided in four themes that are recognizable for urban planners: civil constructions, water, energy and subsurface (Fig. 3).

The Deep City method is a holistic management concept for underground resources. It takes resources (underground space, groundwater, geothermal energy and geomaterial) into consideration in urban development. The utilization of resources is considered in interaction with the synergies and conflicts they may have with other resources. The method also considers institutions for urban management. Just like asset management, the method takes into account both the strategic and operational level. The method consists of six steps: Step 1) (strategic level) Accumulate critical success factors from best practices and select critical success factors of sustainable underground development for urban economy. Step 2 till 5 are on the operational level. Step 2: Collect local urban data for problem diagnostic in underground exploitation, study feasible solutions Step 3: Map the city with different levels of potential, based on comprehensive but simple indicators for public use.

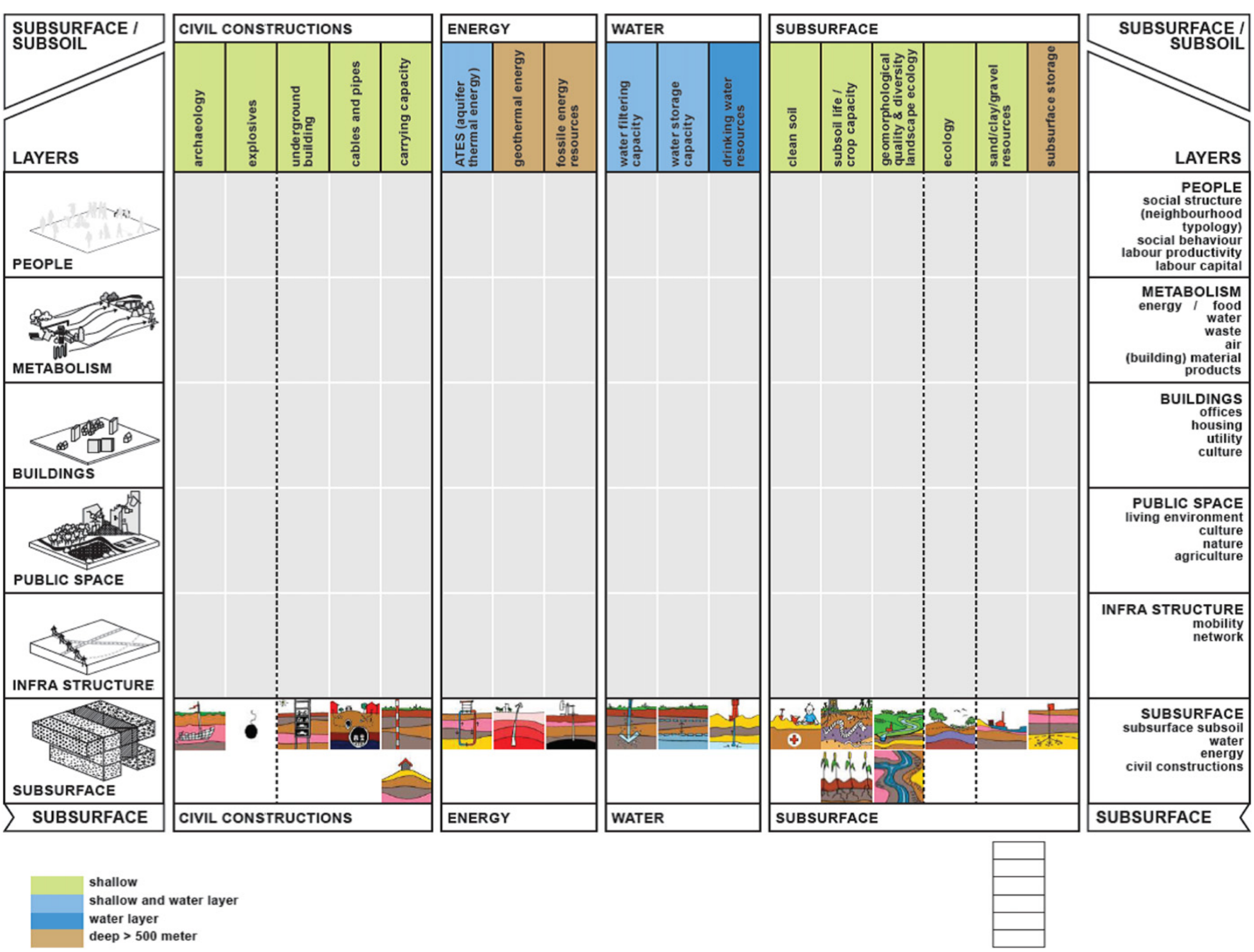


**Fig. 3.** System Exploration Environment and Subsurface (SEES) [4].

Step 4: Assess project typologies, introduce new economic indicators for project evaluation. Step 5: Lever the scenarios based on potential indicators and economic indicators, to guide project implementation, Step 6: (strategic level) Propose new institutional tools or legal instruments to improve the public management process (Li et al., 2013a, 2013b; Doyle et al., 2016).

The Balance4P project, developed on three case studies, developed a holistic approach that supports sustainable urban renewal through the redevelopment of contaminated and/or underused land. This approach aims for better cooperation between urban developers and subsurface specialists in early phases of the redevelopment process. The use of existing tools and better knowledge exchange between involved experts and different phases of the project are crucial for realizing urban planning which considers soil and subsurface functions (Norrman et al., 2015a, 2015b, 2016).

The Urban Sustainable Subsurface Use Methodology (USSUM) methodology combines subsurface characterisation, ecosystem service classification and future scenario analysis. It consists of four main stages: 1) Assessing the beneficial function of the subsurface: Determine functions of the urban subsurface that deliver ecosystem services and the benefits derived from them. 2) Optimisation: Plan for optimised use of the subsurface based on its properties including geological, hydrogeological, geothermal and geotechnical; identify geohazards and geoassets; avoidance of unsuitable subsurface conditions.; use of most suitable subsurface; delivering multiple benefits where possible. 3) Future scenario analysis: Determine sustainability and resilience of a proposed intervention in the subsurface using future analysis. 4) Implementation of proposed subsurface intervention (Price et al., 2016).

The European COST-SubUrban network, a network with municipalities, geological surveys and Research Partners, aimed at improving the understanding and use of the ground beneath our cities. They have developed a toolbox with a fit-for-purpose suite of recommended methodologies, good practices, guidance and case studies to enable the free flow of key subsurface data and knowledge [5].

### 3.3. Risks of the subsurface functions

AMS takes risks into account that can occur due to subsurface use, but also risks that can occur by external use or interventions and that have an effect on the subsurface. Concerning the first, when functions of the subsurface fail, this often has a direct effect on the public space and in direct costs. Failing subsurface functions can have effects such as settlements, delay in building projects, damage to cables and pipelines and flooding. Different activities can also cause risks to the subsurface and its functions. Examples of effects of activities are contamination or soil sealing, disturbing the possibility to use the water storage capacity by land use practices. Another commonly seen example is inefficient use of space or interferences between subsurface functions due to insufficient spatial planning practice (e.g. interfering aquifer thermal energy storage systems).

Both categories of risks can be overcome by performing a (semi-quantitative) risk assessment during projects. Having sufficient data and information of the employed subsurface functions (both natural and man-made), subsurface characteristics and subsurface potential is a requirement to be able to assess and anticipate risks, and prevent them from actually occurring. Unfortunately data and information availability (including quality) and exchange is still insufficient in most cases (Klerk et al., 2015). The Balance4P holistic framework supports and gives guidance for better knowledge exchange between the surface and the subsurface sectors (Norrman et al., 2015a, 2015b, 2016).

### 3.4. Cost and value of subsurface functions

The costs of managing and maintaining man-made assets placed on, or in the subsurface, are high. Not knowing or taking into account the subsurface system, or not managing the subsurface in a sustainable manner, involves high costs. Damage to subsurface assets often occurs due to lacking information or not using information in projects. An example is the damage to cables and pipelines by digging activities, because their location is not registered correctly. On the website of the Dutch Government, it is stated that in The Netherlands repairing costs of cables and pipes are 25 million euro per year [2]. Another example is (preventable) damage to new-placed buildings due to subsidence and flooding because local circumstances were not taken into account in the planning phase. Although the numbers are not known, not fully exploiting the potential of soil functions or irreversibly damaging soil functions can potentially cost society a great lot, now and in the future.

The value of the subsurface, when just considering man-made assets, is large. For example, the Dutch Municipal Platform Cables and Pipes (GPKL) estimated that there is about 2 million km of cables with a replacement value of 100–300 billion euro's in the subsurface in the Netherlands [3]. When taking into account the (indirect/societal) value of functions delivered by the subsurface, this value increases significantly. UN Environment Programme initiative called "The Economics of Ecosystems and Biodiversity" (TEEB) tried to monetize the value of ecosystem services (European Communities, 2008). Some ecosystem services have a concrete economic value for example provisioning services like drinking water, fossil fuels. Unfortunately most ecosystem services have an indirect value. Methods for valuing the indirect benefits of ecosystem services in monetary terms are (e.g. Farber et al., 2002):

1) Avoided cost: services allow society to avoid costs that would have been incurred in the absence of those services (e.g. waste treatment by wetland habitats avoids health costs);
2) Replacement cost: services could be replaced with man-made systems (e.g. restoration of a watershed could cost less than the construction of a water purification plant).
3) Factor income: services provide for the enhancement of incomes (e.g. improved water quality increases the commercial take of a fishery and improves the income of fishers).
4) Hedonic pricing: service demand may be reflected in the prices people will pay for associated goods (e.g. coastal housing prices exceed that of inland homes)

In addition to point 1) and 2), the value and degree of irreversibility and scarcity should be taken into account. When the subsurface and its functions are not planned, used and managed in an optimal manner, potential and future value can be lost. Because subsurface is a slow responding medium, this loss can be irreversible. Scarce and irreplaceable subsurface functions can disappear. In addition of point 3) and 4), the fact that many subsurface functions can be combined with other services should be considered in determining value.

Different studies have been performed to monetize ecosystem services, but putting numbers on the above mentioned values can be difficult and all stakeholders should agree on them. A second difficulty is the division in costs and benefits. Trade-offs can be made on different aspects, but this is location specific. Therefore within AMS the costs and values of functions are semi-quantified by stakeholders in the area, taking into account parameters as irreversible, scarcity and multi-functionality.

## 4. AMS method

The main structure of asset management of the subsurface consists of four steps (Fig. 4), based on ISO 55000 (ISO, 2014). These steps are carried out at two different levels: the strategic and operational level. For both levels, the process is iterative and circular. Boundary conditions for the implementation of AMS are: 1) commitment from the board of directors, including incorporation of asset management process in all organisation layers to make it work at both levels; and 2) continuously measuring, monitoring and communicating the results. By doing so, there is a learning loop and processes can be adjusted in

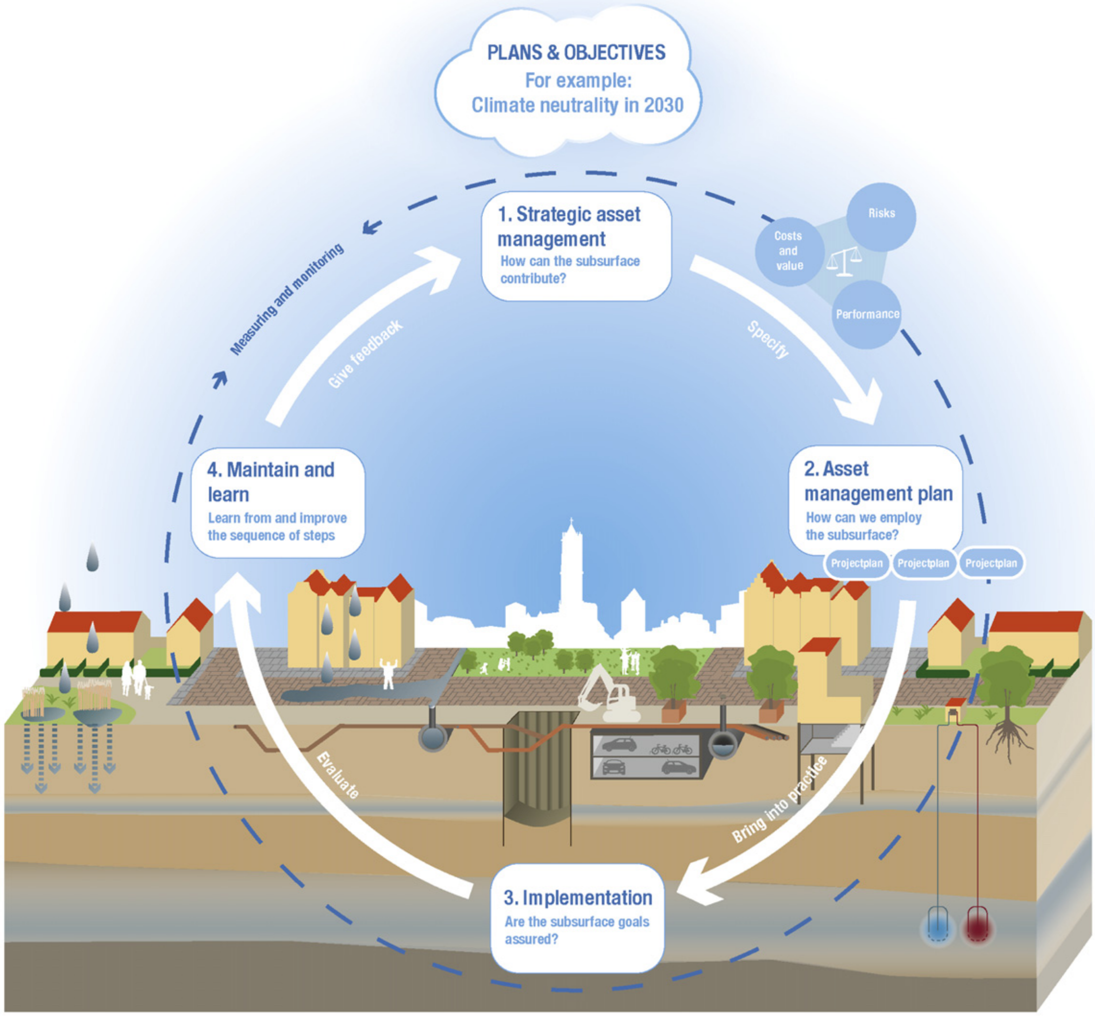


**Fig. 4.** Asset management of the subsurface method.

order to reach the organisational goals effectively. The steps are outlined in the section below and examples are provided in the following sections.

The first step is at strategic level. In this step, plans and objectives (societal ambitions) of the organisation, in this case the municipality, are determined and translated to how the subsurface can contribute to achieve these objectives. This is recorded in a Strategic Asset Management Plan (SAMP). Concrete actions are needed to achieve the required performances of different functions. These actions are well-founded because performance, risks and costs will be balanced. In this stage, asset management transfers to an operational level. The actions are described in an asset management plan (AMP) that ascertains how the subsurface will be utilized to reach organisational goals (step 2). For the subsurface, especially new projects and project plans give a framework to gradually implement AMS. In these project plans, concrete actions and goals for the subsurface can be formulated and eventually implemented. During the implementation phase (step 3) it is important to secure the subsurface goals and communicate plan changes and their consequences. The goals of step 4 are to 1) maintain and manage the function and 2) evaluate and learn from the followed AMS process. Both actions are achieved by continuously monitoring and measuring and subsequently giving feedback (communicate) to improve the AMS method. This feedback loop is essential to further improve and optimize the asset management process within an organisation.

For example: in a municipality's plan the objective of 10% sustainable energy in 2020 is given. The subsurface can contribute to that objective by ATES (Aquifer Thermal Energy) systems. In step 1, this is recorded in the SAMP. In step 2, the potential amount and location of the ATES systems are determined in the AMP. Here demand and subsurface potential for soil energy are specified, as well as other subsurface functions (e.g. supply of groundwater for specific aims). Also potential interferences and combinations can be investigated. In step 3, implementation, the ATES systems are put into operation and maintained. Here, a municipality is dependent on spatial developments and (public and private) projects, where the ATES system can be realized and contribute to the municipality's sustainability goals. The monitoring can in this case simply be done by checking the performance of the ATES systems. When interferences take place, or when the systems are underperforming, action should be taken to ensure the performance of the ATES systems towards the goals of the municipality.

## 5. Challenges

Within the CoP, different challenges in developing the AMS method came across as well as organisational aspects to implement AMS. Some challenges are described below.

Availability of data and information is a challenge. To be able to implement AMS, sufficient, good quality data and understandable

information on subsurface functions, how they interact and react, should be available. By understanding and knowing the urban subsurface system, the potential of subsurface functions can be matched to an area's objectives and unexpected negative effects are avoided. Knowledge exchange, as stipulated earlier in this paper, is vital.

Connected to that, defining the (indirect) value of the subsurface functions is difficult. This is both needed for balancing performance, costs and risks in AMS as well in the communication to other parties concerning the importance of sustainable subsurface management. Factors playing a role are the degree of (ir-)reversibility, possibility for multifunctional uses and scarcity of the function.

The subsurface is currently just one of many aspects in spatial development. Subsurface is a black-box with its opportunities and nuisances, where we just have to deal with. An important challenge is raising awareness of the possibilities in gaining value and decreasing costs when managing the subsurface sustainably. When taking subsurface functions into account with asset management for the public area, conscious decisions can be made whether the subsurface can supply the essential functions, or that this will be solved in another (civil engineering) manner. Value can be added and costs can be avoided when it is recognized that the subsurface is a system and asset management should be tailored to that, instead of maintaining assets of the system separately.

When the decision is made to apply AMS, other challenges rise, related to organisational aspects.

Implementation of AMS asks for a radical change of doing things. The strategic and operational layers in an organisation need to connect and there should be a willingness to set and realize Specific, Measurable, Assignable, Realistic, Time-related, or "SMART" (Doran, 1981) goals and ambitions for the subsurface. It asks for continuous instead of project based management of subsurface and it comprises continuous monitoring and learning.

For AMS, cooperation between disciplines, policy fields and management layers is essential. It is necessary to include different stakeholders from the beginning. In addition, it is important to bridge the gap in language and the way of working between managers, engineers and designers.

The question is who takes, or actually is, responsible for exploiting, managing and maintaining subsurface functions. For many functions there is no "real" asset owner or manager. Public authorities, e.g. municipalities, water authorities and provinces, are in charge by policy and regulation when maintaining and managing subsurface functions. Some functions such as collection of drinking water and archaeology are maintained and managed because there is regulation or a responsible party. Other subsurface functions, such as space or water storage capacity do not have regulation or a direct asset owner or manager. The division of cost and benefits while performing AMS should be considered and balanced in an acceptable way.

## 6. Conclusion

AMS is still in development, but has the potential to become a structured method that gives insight into possibilities, costs and risks, but also the value of the subsurface. Although it can be based on existing subsurface planning, ecosystem and asset management methods, not all principals can be followed one-on-one. The objective is that AMS becomes a structured, sustainable and integral method for subsurface management that is applicable in the municipal daily practice and operational management.

AMS can support decision-makers when choosing between different options to meet objectives and to form well-founded decisions on, if and where to take action and to invest within subsurface management. In this way, private and public investment for subsurface activities can be implemented effectively, realizing the optimal potential of subsurface assets.


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## References


Abspoel, L.M., Courage, W.M.G., Van Den Broeck, W., Kruse, H., Risk based asset management of pipeline networks for gas and water, 2017. Life-cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International Symposium on Life-Cycle Engineering, IALCCE 2016. pp. 1439–1445.

Admiraal, H., Cornaro, A., 2016. Why underground space should be included in urban planning policy – and how this will enhance an urban underground future. Tunnelling and Underground Space Technology. 55, pp. 229–235.

Blumlein, P., Kircholtes, H.J., Schweiker, M., Wolf, G., Schug, B., Wieshofer, I., Huber, Sigbert, Parolin, M., Villa, F., Zelioli, A., Biasioli, M., Medved, P., Vernik, Tomaz, Vrščaj, Borut, Siebielec, Grzegorz, Kozák, Josef, Galuskova, I., Fulajtar, E., Sobocká, Jaroslava, Jaensch, S., 2012. Soil in the City. Urban Soil Management Strategy. ISBN: 978-3-943246-07-0. Department for Environmental Protection, Germany, City of Stuttgart.

De Mulder, E, & Pereira, J J. 2009. Earth Science for the city. 25–31 in Engineering Geology for Tomorrow's Cities. Culshaw, M G, Reeves, H J, Jefferson, I, & Spink, T W (editors). Engineering Geology Special Publications 22. (Bath, UK: Geological Society of London).

Deming, E.W., 1986. Out of the Crisis. MIT Center for Advanced Engineering Study (ISBN 0-911379-01-0).

Doran, G.T., 1981. There's a S.M.A.R.T. way to write management's goals and objectives. Manag. Rev. 70 (11), 35–36 AMA FORUM.

Doyle, M.R., Thalmann, P., Parriaux, A., 2016. Underground potential for urban sustainability: mapping resources and their interactions with the Deep City method. Sustainability 8 (9), 830. https://doi.org/10.3390/su8090830.

Ellen, G.J., van Gaans, P.F.M., Maring, L., van Duijne, H., Blauw, M., Ferber, U., Limasset, E., Smit, M., Bardos, P., Menger, P., 2013. Successful Brownfield Regeneration. EU FP7-HOMBRE Project.

European Communities, 2008. The Economics of Ecosystems & Biodiversity. An Interim Report (ISBN-13 978-92-79-08960-2).

Farber, S.C., Costanza, R., Wilson, M.A., 2002. Economic and ecological concepts for valuing ecosystem services. Ecol. Econ. 41, 375–392.

Hooimeijer, F., Maring, L., 2013. Ontwerpen met de ondergrond. S + RO 2013/6. pp. 52–56 (in Dutch).

ISO, 2014. NEN-ISO 55000: Asset Management - Overview, Principles and Terminology. ISO55000.

Klerk, W.J., van Stokkum, J., Zomer, W., Bakkenist, S., 2015. Generiek framework voor life-cycle management van kritieke infrastructuur. Project ROBAMCI kenmerk: 1220047-002-GEO-Deltares.

Li, H.-Q., Parriaux, A., Thalmann, P., Li, X.-Z., 2013a. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application. Tunn. Undergr. Space Technol. 38:559–568. https://doi.org/10.1016/j.tust.2013.04.010.

Li, H., Li, X., Parriaux, A., Thalmann, P., 2013b. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 2 case study for resource supply and project valuation. Tunn. Undergr. Space Technol. 38:569–580. https://doi.org/10.1016/j.tust.2013.04.009.

Metje, N., Rogers, C.D.F., Chapman, D.N., 2008. Seeing Through the Ground - Mapping the Underworld Project (2008). 12th International Conference on Computer Methods and Advances in Geomechanics 2 pp. 1502–1508.

Millennium Ecosystem Assessment (MA), 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington.

Norrman, J., Volchko, Y., Maring, L., Hooimeijer, F., Broekx, S., Garção, R., Kain, J.-H., Ivarsson, M., Touchant, K., Beames, A., 2015a. Balance 4P: Balancing Decisions for Urban Brownfield Regeneration – Technical Report. Report 2015:11. Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Norrman, J., Maring, L., Hooimeijer, F., Broekx, S., Garção, R., Volchko, Y., Kain, J.-H., Ivarsson, M., Touchant, K., Beames, A., 2015b. Balance 4P: Balancing Decisions for Urban Brownfield Regeneration – Case Studies. Report 2015:12. Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Norrman, J., Volchko, Y., Hooimeijer, F., Maring, L., Kain, J.-H., Bardos, P., Broekx, S., Beames, A., Rosén, L., 2016. Integration of the subsurface and the surface sectors for a more holistic approach for sustainable redevelopment of urban brownfields. Sci. Total Environ. 563-564:879–889. https://doi.org/10.1016/j.scitotenv.2016.02.097.

Otte, P.F., Maring, L.M., de Cleen, M., Boekhold, S., 2012. Transition in soil policy and associated knowledge development. Current Opinion in Environmental Sustainability. 4. Elsevier :pp. 565–572. https://doi.org/10.1016/j.cosust.2012.09.006.

Price, S.J., Ford, J.R., Campbell, S.D.G., Jefferson, I., 2016. Urban Futures: The Sustainable Management of the Ground Beneath Cities. 27. Engineering Geology Special Publications:pp. 19–33. https://doi.org/10.1144/EGSP27.2.

Shah, J., Jefferson, I., Ghataora, G., Hunt, D., 2014. Resilient Geotechnical Infrastructure Asset Management. Geotechnical Special Publication, (234 GSP):pp. 3769–3778 https://doi.org/10.1061/9780784413272.365.
United Nations, Department of Economic and Social Affairs, Population Division, 2014. World Urbanization Prospects: The 2014 Revision.

## Web references

European Environment Agency, 2014]. The Common International Classification of Ecosystem Services CICES Version 4.3. https://cices.eu, Accessed date: 19 July 2017.
Rijksoverheid, ]. https://www.rijksoverheid.nl/onderwerpen/bodem-en-ondergrond/graafschade, Accessed date: 31 August 2017.
Dutch Municipal Platform Cables and Pipes, ]. http://www.gpkl.nl/page/144/kengetallen.html, Accessed date: 19 July 2017.
System Exploration Environment and Subsurface (SEES), ]. https://publicwiki.deltares.nl/display/SEES/HOME+English, Accessed date: 19 July 2017.
http://sub-urban.squarespace.com/toolbox-1/, Accessed date: 31 August 2017.